

Roadmap For Small Bodies Exploration: Theoretical Studies

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This document covers five broad topics from theory of small bodies: planetesimal formation, cosmochemistry, thermal evolution, collisions and dynamics. Each of these topics is described in a separate section, where we prioritize selected main issues over completeness. The text points out the principal unresolved problems in each area, and suggests ways how progress can be made. This includes support for new code development, observations and experimental work that can be used to constrain theory, new research directions, and studies of cross-over regimes where the system's behavior is determined by several competing processes. The suggested development areas are placed in the context of NASA space exploration.

1. Planetesimal Formation

A primary rationale for small bodies research is to improve our understanding of how planetesimals form — a vital step in the growth of terrestrial and habitable planets. To maximize the scientific return from exploration missions, it is imperative to support theoretical work on planetesimal formation. It is also beneficial to adapt mission designs to address pressing theoretical issues, when feasible and well-justified. As a concrete example, since equal mass Kuiper belt binaries are a sensitive probe of formation models, a New Horizons encounter with such a system is well-motivated.

Broadly speaking there are two ways to improve theories of planetesimal formation. The first is to improve our understanding of the fundamental physical processes at play. The second is to fit observed properties of small bodies to a phenomenological model by varying uncertain parameters. These approaches are not mutually exclusive, but in reality compromises must be made. Studies of physical processes may lack all the necessary ingredients

— or computational resources — to match reality. Models built to match data may include physically unjustified assumptions. Pursuing studies that correctly weight both approaches will lead to the greatest scientific progress.

1.1. Formation Theories

The textbook theory that planetesimals formed by orderly collisional growth is becoming increasingly questioned. Both experiments and theoretical arguments have highlighted the low efficiency of sticking in the millimeter to meters size range. This has coincided with a burst in progress in dynamical formation mechanisms to trigger planetesimal formation by gravitational collapse, as described below. However these dynamical models only intensify the need to understand collision outcomes. The extent to which collisional growth proceeds towards centimeter sizes, or possibly beyond, remains a key uncertain input to the dynamical models. For larger planetesimals, however they may form, ongoing collisional evolution (see §4) must be included for comparison with observations.

The initial version of the gravitational hypothesis was proposed by Safronov (1969) and Goldreich & Ward (1973). The critique by Weidenschilling (1984) of the model significantly advanced the study of nebular dynamics. He argued that vertical shear instabilities in the disk midplane would trigger turbulence that halts the vertical sedimentation of particles to the midplane. Consequently, densities should be too low for direct gravitational collapse. Subsequent work, notably by Cuzzi, Dobrovolskis & Champney (1993) confirmed this obstacle. The seriousness of the obstacles to both gravitational collapse and collisional growth left planetesimal formation theory in a difficult position.

Advances in dynamical studies now offer possible resolutions. Sekiya (1998) and Youdin & Shu (2002) showed how vertical shear instabilities were weakened when the ratio of solids-to-gas was enhanced above Solar abundance values, offering a route to gravitational collapse. This mechanism is supported by the finding that extrasolar planets are more abundant around high metallicity stars, which presumably had dustier protostellar disks. However the issue remained for how to enhance the abundance of solids relative to gas in disks around Solar-type stars.

Many mechanisms have been proposed for the aerodynamic concentration of solids in a gas disk. These include gaseous spiral arms, persistent vortices, photoevaporation of gas, pileups of solids due to radially varying drift rates. Cuzzi et al. (2001) proposed that turbulence, typically thought of as a stirring agent, could also concentrate solids on the scale of eddies due to centrifugal expulsion. The mechanism has advantage of efficiently concentrat-

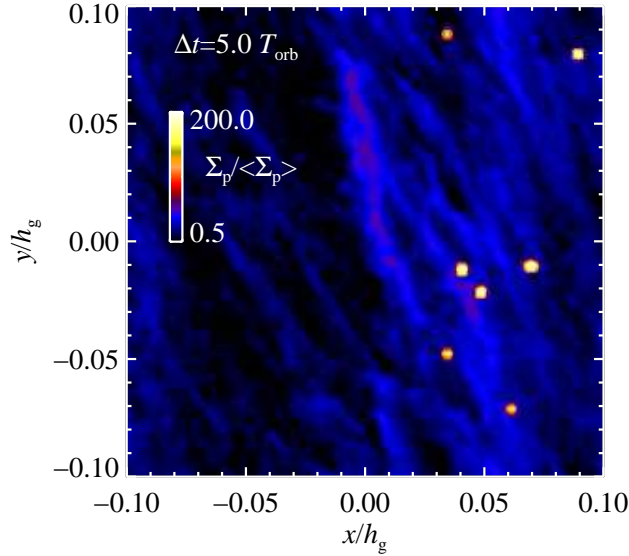


Fig. 1.— Particle column density, Σ_p , showing the formation of seven gravitationally bound clumps in a 3D, vertically stratified, shearing box simulation of unmagnetized gas and superparticles with stopping time 0.1–0.4 (Johansen, Youdin & MacLow 2009). The initial box-averaged particle-to-gas density $\langle \Sigma_p \rangle / \langle \Sigma_g \rangle = 0.02$. The $x(y)$ axis is parallel to the radial (azimuthal) direction, and measured in units of the gas scale height. The simulation first evolved for 40 orbits without self-gravity, during which particles settled to the midplane and triggered vertical shearing and streaming instabilities; strong clumping resulted. This snapshot is taken 5 orbits after self-gravity was turned on. The bound fragments contain $\sim 20\%$ of the total mass in solids; each has a mass comparable to a compact planetesimal having a size 100–200 km. Figure from Johansen, Youdin & MacLow (2009).

ing mm-sized solids for reasonable assumptions about the turbulence. By contrast the other mechanisms mentioned above work best on larger, meter-sized solids. The size difference reflects the aerodynamic coupling or stopping timescale. For meter sizes, the stopping time is just orbital timescale, which is the most relevant for most dynamical processes. However fast-swirling eddies interact with smaller solids that have a shorter stopping time.

The streaming instability (SI) is a powerful and “active” clumping mechanism that arises spontaneously due to drag forces in disks. By contrast the above-mentioned clumping mechanisms are “passive” since particles respond to an assumed flow of the gas. While discovered analytically by Youdin & Goodman (2005), numerical simulations of the SI by Johansen, Youdin and collaborators (Johansen & Youdin 2007; Johansen, Youdin & MacLow 2009) revealed that SI clumping amplitudes are large enough to trigger gravitational collapse

(Fig. 1). The strongest clumping amplitudes are seen for ~ 10 cm solids. While smaller solids appear to clump less efficiently — as reinforced by the simulations of Bai & Stone (2010) — numerical difficulties with small stopping times are still a factor. One hope is that the small scale clumping described by Cuzzi et al. (2001) could interact constructively with SI, but this is still difficult to simulate directly.

A surprising finding of recent work is that planetesimals which form by gravitational collapse could be many hundreds of kilometers in radius. This is much larger than the canonical value of several kilometers from Goldreich & Ward (1973) because collapse begins at much larger densities due to aerodynamic clumping. Johansen et al. (2007) formed 1000 km radius equivalent (since the collapse did not proceed to solid densities) bodies in simulations with SI clumping and forced (by magnetic fields) turbulence. Johansen, Youdin & MacLow (2009) found 100-200 km (equivalent) radius planetesimals from SI clumping of slightly smaller solids and no forced turbulence, i.e. only turbulence driven by particle-gas interactions. A more complete survey of parameter space will help understand these dependencies and lead to predictions of initial size distributions.

Cuzzi, Hogan & Shariff (2008) argued that the small scale clumping by forced turbulence could also extend to larger scales and produce 100 km scale planetesimals. While this conjecture is not amenable to direct simulation, the theoretical basis of the scaling arguments can be developed.

1.2. Discriminant Tests of Formation Theories

Different planetesimal formation theories should have different implications for the properties of small body populations. For example, the gravitational collapse has the potential to quickly create objects with characteristic large size, while two-body collisions may lead to more gradual growth and result in a more continuous size spectrum. Progress toward discriminating between different formation theories can therefore be made by carefully comparing the theoretical predictions with properties of asteroids and Kuiper belt objects (KBOs). Unfortunately, except of the recent work by Schlichting & Sari (2011), who estimated the initial size function (ISF) of KBOs for the standard growth by two-body collisions, detailed theoretical predictions are not generally available (see also Cuzzi et al. 2010).

While it may be possible to derive ISF of planetesimals from analytic scaling arguments, the analytical work is more likely to be valuable elsewhere, for example when identifying (and characterizing) the principal physical processes that contribute to planetesimal formation. Reliable IMF predictions will instead be most likely obtained from numerical simulations

that are probably more amenable to incorporating the complex physics of non-linear solid-gas coupling. Presently, however, the predictive power of simulations is still strongly limited by large CPU requirements that stem from need to have both the detailed resolution and global coverage of disk processes. Support should thus be given to the development of new, more efficient numerical codes that will be able to speed up calculations and allow scientists to more fully explore parameter space.

The theoretical suggestion that planetesimals could form big very quickly found support in Morbidelli et al. (2009), who argued that the size distribution of the largest asteroids is likely imprinted by the collapse process. This conclusion arises from the difficulty of explaining the size distribution of large asteroids with standard collisional growth. While suggestive, this work also illustrates the difficulty in discriminating between formation and evolution processes. This is because the ISF can be modified by disruptive collisions and dynamical depletion processes occurring since planetesimal formation 4.6 Gy ago. For example, it is believed that most asteroids with radius $R < 10$ km are fragments of disruptive collisions (Bottke et al. 2005), while the population of large asteroids may have been depleted by a factor 10-1000 by dynamical processes (Petit et al. 2002). Understanding the evolution processes is thus an important issue that arises when it is attempted to derive ISF from observations, and support should be given to those who seek funding for such a research.

While KBO populations also show characteristic size distributions that can arise from the formation process, the evolution history of the KBOs is significantly more uncertain, making interpretation difficult. Specifically, it is not well understood whether the cold classical KBOs, a dynamical component between 42-48 AU having low eccentricities and low inclinations, formed in situ at 42-48 AU or was implanted in that region from elsewhere (Levison et al. 2008). The size distribution shape of cold classical KBOs with $R > 10$ km is similar to that of the main belt asteroids, showing a break at $R = 50$ km. The break can suggest ISF with a preferred size of planetesimals with $R = 50$ km (Nesvorný et al. 2010a, 2011), or can be a signature of disruptive collisions that depleted the population of objects with $R < 50$ km (Pan & Sari 2005). This issue is of crucial importance for the planetesimal formation theories in the outer solar system.

2. Cosmochemistry

We focus on Ceres in this section because it is one of the nearby objects that can potentially show interesting chemistry that is relevant to planet formation. Moreover, with the Dawn mission, we have the real opportunity to use Ceres as a chemistry lab and calibrate

our cosmochemical models.

Ceres, the largest asteroid in our Solar System, is a keystone for astronomers trying to reconstruct the growth histories of planets. A member of asteroid class C (carbonaceous), its spectrum shows evidence of organic compounds on its surface. Furthermore, Ceres bulk density of only 2.08 g cm^{-3} (Thomas et al. 2005) indicates that it contains up to 30% water ice by mass. The abundance of both water ice and organics in Ceres provides evidence that it formed in a cold part of the Solar Nebula –the disk of raw planet-forming material that surrounded the young Sun– where volatile compounds such as water and ammonia could freeze. Since each “ice” has a different characteristic temperature at which it clings to planet-building dust particles, measurements of the compositions of icy asteroids contain a fossil record of the planet-forming environment.

Although astronomers have predicted the mass fraction of ices in Uranus and Neptune (Hubbard et al. 1995, Dodson-Robinson & Bodenheimer 2010), most of the heavy elements in gas giants are locked deep in their interiors, invisible to observers. By contrast, C-class asteroids such as Ceres are ideal proving grounds for theories of planet formation because they can hold ices on their surfaces. NASA’s Dawn spacecraft, with its Gamma Ray and Neutron Detector (GRaND), is already en route to the asteroid belt and will reach Ceres in 2015 (Rayman et al. 2006). GRaND will map out the atomic composition of Ceres’ surface, allowing astronomers and geophysicists to determine Ceres’ ice inventory and temperature distribution and reconstruct its evolutionary history.

Chemical evolution models can maximize the potential of the Dawn Mission by computing the abundances and distributions of ices in Ceres from initial freezeout through asteroid growth and cooling. By determining the range of possible surface compositions for Ceres today, cosmochemical analysis will allow the GRaND instrument to make the leap from present-day composition to planetary archeology: its data will help us determine the correct asteroid formation pathway among many possibilities.

Following is a brief list of possible formation scenarios and associated observables for Ceres, based on the solar nebula models of Dodson-Robinson et al. (2009) and the asteroid geophysical models of Castillo-Rogez & McCord (2010):

1. Although pure ammonia has an extremely low freezing point, ammonia-water mixtures may deposit on dust surfaces at much higher temperatures. Ceres may contain up to 7% ammonia by mass. (Fig. 2). The presence of ammoniated minerals would suggest that water and ammonia formed a mixed ice matrix during Ceres’ formation. Incorporation of ammonia into water ice would allow subsurface ocean formation on small bodies

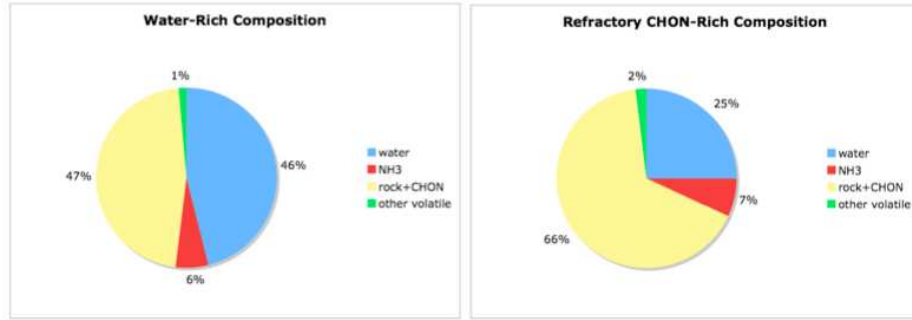


Fig. 2.— Ceres’ current composition may have evolved from an initially water-rich chemical inventory (left), where water was lost due to internal heating. It is also possible that water loss over time was negligible and Ceres’ initial and present-day compositions are similar (right). The difference in initial water abundance between the two models pictured is due to different assumptions about the sequestration of carbon in solid (refractory) grains versus lightweight, volatile hydrocarbons. GRaND measurements may distinguish between these two models.

more distant from the Sun, as ammonia lowers the melting point of water. Ganymede, Callisto, Titan and Enceladus are all predicted to have subsurface oceans (Spohn & Schubert 2003, Hussmann et al. 2006, Lopes et al. 2007).

2. Ceres accreted almost 50% water ice by mass (Fig. 2). A key question is about the fraction of that water: bound to minerals (e.g., hydrated silicates and salts) and that amount available to form an icy shell. The large-scale migration of water through the asteroid might have created hydrated minerals on Ceres’ surface that are observable today. Ceres may even be experiencing volatile loss today, similar to the outgassing from asteroid Lutetia observed by the ROSINA experiment aboard Rosetta (Wurz et al. 2010).
3. Although much of the organic material on Ceres’ surface is likely graphite and kerogen, some of it may be hydrocarbons such as acetylene and ethane. Hydrocarbons on Ceres’ surface would provide strong evidence that Ceres’ formation zone was colder than 60 K.

An inventory of the organic material on Ceres’ surface is especially important in light of the recent discovery that Allende’s remnant magnetization was most likely imprinted by the convecting metallic core of a partially differentiated parent body (Weiss et al. 2010). Elkins-Tanton et al. (2010) argue that chondritic meteorites are not remnants of pristine bodies but are instead parts of the unmelted mantles of partially differentiated asteroids. Indeed, ongoing analyses of Rosetta observations will reveal whether (21) Lutetia has the

high density and CV-like surface that characterize the disrupted CV parent body. Ceres and Pallas both have shapes and bulk densities consistent with partial differentiation.

Volatile retention implies late formation relative to the formation of the Sun and the CAIs for two reasons: (1) the inner solar nebula must cool enough for ices to freeze, and (2) ^{26}Al decay leads to volatile loss. However, partially differentiated asteroids are thought to be members of an early generation of planetesimals. A differentiated yet volatile-rich asteroid such as Ceres may point to an extremely brief planetesimal formation epoch, at least in the inner solar system. Castillo-Rogez & McCord (2010) have already begun pinpointing Ceres’ formation time relative to the CAIs. Ceres shape data, gravitational field measurements and surface composition inventory from Dawn will therefore be critical to exploiting Ceres’ potential as a planet formation chronometer.

3. Thermal Evolution Models

Traditionally, thermal evolution models of small bodies are divided into three subclasses:

1. Early thermal evolution of a hypothesized CI/CM parent body (see Figure 3; radius $R = 50$ to 100 km) composed of ice and rock to determine conditions under which silicates in their interiors are hydrothermally altered, with the goal of deducing what the mineralogy of CI and CM meteorites tells us about conditions in the early solar system (e.g., Grimm & McSween 1989, Travis & Schubert 2005).
2. Early thermal evolution of rock/metal bodies such as Vesta ($R \sim 265$ km), focusing on chemical and physical differentiation and petrogenesis, with the goal of understanding the composition and mineralogy of HED meteorites (e.g., Gosh & McSween 1998).
3. Thermal evolution of comets ($R \sim 5$ km) due to insolation, radiogenic heating, formation and breakdown of clathrates, and ice phase changes in present-day conditions with the goal of understanding the timing, duration, and magnitude of outgassing events (see Prialnik 2000 for a comprehensive summary).

In such models, ice/rock bodies have a period of early activity driven by accretional heating and decay of short-lived radioisotopes (SLRI; ^{26}Al , ^{60}Fe). These early heat sources drive differentiation of the primordial ice/rock mixture into a consolidated central rock core. The rock core heats by short-lived radiogenic heating, and later by ^{40}K heating, and may

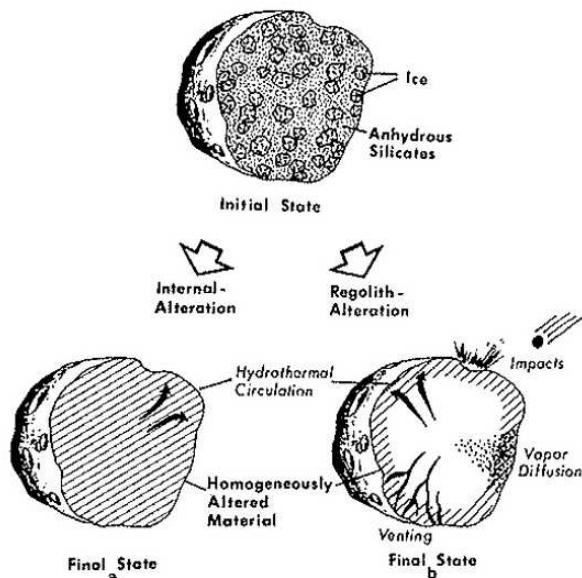


Fig. 3.— Schematic illustration of the processes that shape the interiors of small bodies, focused on the CI/CM parent body (Grimm & McSween 1989), including hydrothermal alteration of silicates in the body’s interior, hydrothermal circulation driven by interior temperature gradients, vapor diffusion in the body’s interior, venting through surface cracks, and impacts.

dehydrate, liberating even more energy. Heat transport in the overlaying ice mantle occurs by solid-state conduction, hydrothermal circulation and/or diffusion of water vapor through mantle pore spaces. The formation and evolution of a porous insulating regolith at the surface plays a key role in raising the interior temperatures of small bodies. The evolution of rock/metal bodies such as Vesta also experience a period of early activity driven by SLRI heating, which leads to differentiation, melting and crustal formation.

Small body models are distinguished from thermal evolution models of solid planets and planetary satellites by their inclusion of heat and mass transport through diffusion or circulation of fluid or vapor through interior cracks or void spaces. In large solid planets or satellites, these processes are thought to be important only in the outer few kilometers where lithostatic pressures are too low to close cracks and voids.

Small body models typically focus on a single burst of activity early in the body’s history, immediately after formation. By contrast, thermal evolution models of solid planets and satellites typically focus on heat transfer over billion-year time scales and assume that the system has forgotten its initial condition (appropriate for a diffusive/convective planetary

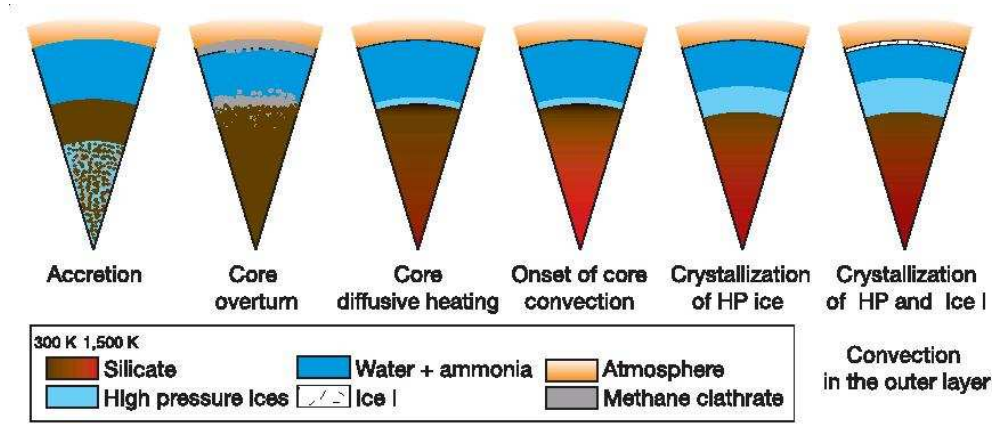


Fig. 4.— Global thermal processes at work inside a large icy satellite, in this case, Titan (Tobie et al., 2006). After accretion of a cold mixed ice/rock core overlain by a layer of pure rock, the deep interior of the satellite is gravitationally unstable, and an initial core overturn is triggered (left). The core is heated from within by decay of long-lived radioisotopes and eventually convection begins in the core (middle). As the satellite cools, layers of high-pressure ice phases and ice I form at the top of the core and surface of the satellite, respectively. Unlike the “small body model” in Figure 3, hydrothermal circulation, vapor diffusion, and other processes that advect mass through interior voids and cracks are ignored.

interior; Fig. 4).

However, the line between small bodies and large planetary objects has been blurred by, for example, the discovery of the water-rich composition of Ceres ($R = 475$ km), and geological diversity of Saturn’s small ice/rock moons (radii range between 200 to 750 km). In particular, Enceladus ($R = 252$ km) has a geologically active region at its south pole driven by tidal heating (Schubert et al., 2007; Nimmo et al., 2007) characterized by large heat fluxes and ongoing degassing from its interior (Porco et al., 2006). Outermost Iapetus ($R = 764$ km) has a peculiar shape indicative of an early period of rapid rotation, and a 20-km-high equatorial ridge. Discovery of the incomplete differentiation of Callisto ($R = 2410$ km; Anderson et al. 1998) and Rhea (Anderson & Schubert 2007; Iess et al., 2007) suggests that SLRI and accretional heating in these objects was limited (Barr & Canup 2008), providing clues about the timing and duration of their formation.

Accordingly and perhaps appropriately, the boundary between thermal evolution models of small bodies and planetary satellites has begun to blur. Processes typically reserved for small bodies may play a role in the geochemical and geophysical evolution of planetary satellites, and vice versa.

As an example, one model proposed for the plume activity on Enceladus suggests that the observed abundances of water and other species in the plume can be explained by clathrate degassing (Kieffer et al., 2006). Solid-state convection, typically thought to occur exclusively in large planetary objects, may play a role in driving activity on Enceladus (Roberts & Nimmo 2008; Barr 2008). SLRI heating and mantle porosity have been invoked to explain the early thermal evolution of Iapetus (Castillo-Rogez et al., 2007).

A removal of the artificial boundary between small body and planetary satellite models is well justified by recent spacecraft observations. Improved numerical methods, e.g., coupled models of hydrothermal and thermal convection (e.g., Travis & Schubert 2005) can help remove the boundary between these fields.

However, uncertainties about the material properties of ice and rock at planetary conditions have led to uncertainties about which physical processes occur inside a given body. For example, solid-state convection is difficult to start, but can occur in the 100 kilometer-thick ice mantle of Enceladus (Barr & McKinnon 2007). McCord and Sotin (2005) also demonstrated that convection onset is possible in the case of Ceres.

Castillo-Rogez and McCord (2010) pointed out the complexity of convection modeling in the case of Ceres, because of the abundant amount of impurities expected in the early ocean as a consequence of intense hydrogeochemistry promoted by SLRI decay. A large amount of impurities is expected to affect the structure of the shell. Kargel (1991) showed that thick layers of hydrated salts that precipitated at the base of an icy shell (asteroid or icy satellite) may be subject to cryovolcanism. This was modeled in more detail by Prieto-Ballesteros and Kargel (2005) in the case of Europa.

Thus, laboratory experiments must be encouraged and supported alongside new theoretical model development. In particular, measurements of the porosity, thermal conductivity, yield strength, and viscosity of pure ice and ice/rock mixtures at confining pressures appropriate for small- to mid-sized ice/rock bodies are urgently needed. These will give modeling efforts a new level of realism and modelers confidence in their results.

4. Impact Studies

Asteroids, comets and small satellites evolve physically in response to cratering impacts and more energetic collisions. The small bodies we see today are, for the most part, collisional disruption remnants derived from the ancestral populations of bodies that formed 4.6 billion years ago, whose characteristics and sizes remain poorly known, and which formed by accretionary processes involving slower collisions (as discussed in §1). Meteorites from small

bodies are delivered by the thousands to Earth by more recent impacts.

Understanding impacts and collisions is fundamental to understanding small bodies, and five approaches are taken:

1. simulations based on physical integrations (computer models)
2. theoretical approaches based on conservation laws and scaling
3. experimental studies in impact chambers, centrifuges, quarries, parabolic flights and drop towers, and (soon) sub-orbital laboratory flights
4. direct observation (natural collisions, and space missions like Deep Impact)
5. physical and petrological studies of meteorites

4.1. Simulations

Computer simulation is a rapidly advancing modern tool that unites theory and experimentation. Here it is most crucial to benchmark these physics-based algorithms to lab experiments, analytic solutions, and astronomical and spacecraft observations. It is not enough to conserve mass, momentum and energy, and it is not sufficient to prove (say) that the method is 2nd order accurate. Computer models of small body impacts and collisions are applied to untested domains and as with any software unexpected errors much be expected until the behavior in the relevant problem domain is fully understood. Most notoriously, the equation of state (EOS) can meddle with the integration by doing unanticipated things to the sound speed, or to the internal energy. Or, the application of a low-density cutoff or a sound speed minimum can suppress shocks. High resolution may be required to capture important aspects of the physics and in 3D may not be achievable in near future.

To the extent that computer simulation is sometimes called the ‘third branch of science’ benchmarking cannot be emphasized enough. The strange environment of small body impacts (the nonintuitive dominance of gravity; the Coriolis forces; the influence of aggregate cohesion; the trapping of seismic energy) makes it difficult to decide whether or not a simulation has produced reasonable results, or has run to late enough time. But once properly benchmarked, a simulation allows us to conduct numerical experiments that lead to understandings of planetary processes at scales far beyond what is attainable in the laboratory, and in regimes far too complex for theoretical analysis alone. In the coming decade we can make very substantial progress if we pay attention to the pitfalls of numerical modeling.

A number of primary computer codes are used for simulations of small body impacts and collisions. Continuum codes include smoothed particle hydrodynamics (SPH; Benz & Asphaug 1995, Jutzi et al. 2008) and various grid based codes such as CTH (e.g. Housen & Holsapple 2003, Leinhardt & Stewart 2009). These codes often include relatively crude rheological models (strength, friction) which may not adequately capture microgravity behavior especially at the very low strain rates and stresses governing the end-game of global-scale cratering (Asphaug & Melosh 1993). Another limitation is computer power, where high resolution 3D runs are feasible, or runs to late time, but seldom both. The post-impact flow field may require an hour or more to evolve in response to a collision (the gravity timescale), whereas the sound-crossing time on a small body can be less than a second. This discrepancy means that millions of model timesteps (a resolution element divided by the sound speed) may be needed to simulate an impact or collision to late time, easily tying up a modest computer facility for days, and producing unwieldy data sets. The bigger the impact event, the easier it is to model from a numerical point of view, because the sound crossing time becomes comparable to the collision time; this creates a situation where impacts into small bodies must strive to obtain time on massive supercomputers, a problem similar in scope to the challenge to obtain time observing diminutive asteroids on large facility telescopes.

Particle codes are also applied to model rigid bodies such as spheres or collections of polyhedra, applicable at events that are slow enough to allow for rigid-body treatments of their constituents (e.g. Richardson et al. 2002, Korycansky & Asphaug 2006). Action is instantaneous so these models run quickly. Sometimes particle codes are included in hybrid schemes where a continuum approach is used to evolve the early stages of an impact, and a granular N -body code is used to evolve the late stages (e.g. Michel et al. 2001). Here the cutting edge is the influx of new techniques adopted from the granular physics community, where the rigid body approach is being supplanted by elastic-dashpot and van der Waals forces, and the achievement of very high resolution simulations that can model a rubble pile out of realistically small grain sizes to reveal aggregate phenomena.

Continuum and particle codes have been applied to study asteroid catastrophic disruption and family formation, formation of binary systems, hit-and-run collisions, evolution and loss of regolith, and impact shock alteration. Often the simulations are at the cutting edge of what is achievable. Looking to the advent of very inexpensive supercomputing on GPUs (graphics cards) in the coming decade, we shall soon be able to trace the detailed impact response in 3D targets with realistic compositions and structures, to late time. While laboratory benchmarking is essential, meteorites serve as their own benchmarks. For instance, impact modeling can be tied to meteorite constraints such as the shock/degassing levels of ordinary chondrites and other types of meteorites. As we push to higher and higher resolution, treatments at the continuum level (sub-grid-scale porosity, fracture damage and mixed

phases) will evolve into treatment at the explicit level (real voids or zones of damage in the grid, and zones of different composition). But the path from here to there is not straightforward. An order of magnitude increase in computer performance means a factor of ~ 2 increase in 3D model resolution, so by Moore’s law every 10 fold increase in 3D resolution requires ~ 15 years. Moreover, to date every leap in resolution has given a slightly different answer to a number of the more detailed modeling problems. Computer models guide and extend our intuition but are not yet, except in a few well-posed domains, a replacement for direct observation and theory.

4.2. Theoretical Approaches

The scaling of crater dimensions applies to asteroids as well as it does to the surfaces of planets, although for large craters vector \mathbf{g} is not nearly a constant g_z . On most small bodies seen to date, a crater diameter is achieved that is comparable in diameter to the target, and no good theory exists to account for craters in this size regime. The global impact response is very poorly understood, in varying gravity and finite geometry where the surface curvature is comparable to the crater diameter, and where trapped vibrations can modify the crater even as it is forming. A fundamental problem is that useful scaling models assume that either strength or gravity (but not both) dominate the collisional response; data suggest that this is not the case for small bodies, where gravity is minuscule yet where so much of the post-impact morphology looks gravity-controlled, and where strength may be ‘hiding’ in the form of granular cohesion (Scheeres et al. 2010).

Accretion involves collisions between objects that are comparable in size, at velocities comparable to or slower than their mutual escape velocity. At the small end, early on, these may have involved ~ 10 km bodies crashing together at meters per second; at the large end, the so-called late stage, it is believed that Mars sized planets collided with proto-Earth. Smaller-scale accretionary collisions occur at the speed of a car crash and involving undifferentiated materials – a quite unstudied physics.

The path forward is to extend, and perhaps look beyond traditional scaling approaches, by examining the results of new observations and simulations, perhaps adapting theoretical models from companion sciences such as seismology and granular physics.

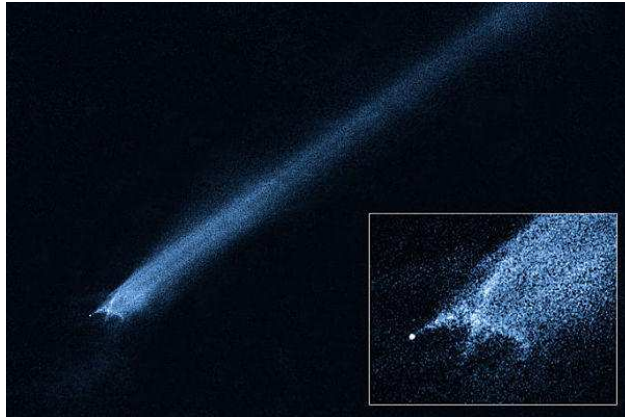


Fig. 5.— Hubble Space Telescope observations of inner-belt asteroid P/2010 A2 show a peculiar comet-like morphology. The data reveal a nucleus of diameter ≈ 120 meters with an associated tail of millimetre-sized dust particles. It is most probably a remnant of asteroidal disruption in February 2009, evolving slowly under the action of solar radiation pressure (Jewitt et al. 2010, Snodgrass et al. 2010). Figure from Jewitt et al. (2010).

4.3. Experimental Studies

The near future promises inexpensive access to low-Earth orbit, with research-project class suborbital flights providing 15 minutes or more of clean microgravity. These relatively low-cost flights will allow microgravity impact (and blast analog) experiments at cm- to possibly m-scale, providing data in a controlled environment that is likely to be closely relevant to the 100-m to km-scale events on asteroids, both those occurring naturally and those being triggered by artificial means.

At a small NEO, a subspacecraft “pod” with total mass less than 10 kg might be expected to deliver enough blast efficiency to produce a ~ 100 m diameter crater on an asteroid the size of Itokawa (~ 300 -500 m diameter), in a medium-class NASA mission where an orbiter monitors the event. Crater formation would take hours. The comparable event can be studied (if gravity-scaled) in a suborbital flight, but this would also take hours. Because ballistic and explosion studies do not mix well with human spaceflight, a robotic orbital research platform for NEO studies would be effective for conducting experiments bridging the strength and gravity regimes.

4.4. Direct Observation

Until an impact between two small planetary bodies is directly observed, we can study the aftermath in various forms: the cratering record on small bodies; the asteroid families which derive from catastrophic disruption events; the dust-brightening observed for a few asteroids that are probably due to recent impact (Fig. 5); and (if one counts tidal collisions) the gravitational disruption of comets by Jupiter.

Great inroads have been made relating asteroid family formation to the process of catastrophic disruption (Michel et al. 2001, 2002, 2003, Nesvorný et al. 2006, Durda et al. 2004, 2007). Larger telescopes, and more telescope time spent on small bodies, have enabled detailed spectroscopy at high time resolution to understand spin rates, shapes, and compositional and thermal characteristics of family members formed millions of years ago. With the advancement of synoptic sky surveys such as LSST it shall become possible to witness the aftermath of small bodies in the days or weeks following the smaller-scale collisions that occur sporadically.

Spacecraft make detailed observations of the cratering record of small bodies, revealing global and regional responses, notably the seismic shaking by impact of pre-standing topography which can be used to derive the mechanical response to impact. The cratering record of a number of close-approaching NEOs have also been detected by radar telescopes at Arecibo and Goldstone (e.g. Benner et al. 2002), greatly leveraging the few spacecraft encounters. Active missions allow for direct monitoring of the cratering process in micro-gravity, and successors to Deep Impact shall conduct observational campaigns from orbit (see §4.3).

4.5. Meteorites

Meteorites are blasted off from asteroids and (sometimes) from the Moon and Mars by impacts. Closely related is the interstellar dust that may have formed on comets. Meteorites formed originally in the collisional processes that created asteroids, and evolved on their parent bodies, showing signatures of many kinds of collisional processing. In the coming decade, for progress to be made in either field - the study of meteorites, and of small body impacts and collisions including the formative ones - a closer kinship is required between these sciences, which have advanced distinctly yet, for the most part, separately over the past decade, to the point that most meteoriticists are outsiders to impact studies and vice-versa. Fewer scientists ‘bridge the gap’ between both disciplines, as was more feasible 20-30 years ago when both disciplines were smaller. A regular workshop on the collisional origin

and evolution of meteorites and their impact delivery to Earth is recommended.

5. Dynamics

While significant progress has been made in understanding the dynamical evolution of small bodies, there remain areas where progress needs to be made. This arises in part due to the interesting and unforeseen configurations and morphologies of small body systems that are being discovered by observational astronomers. These include binary and triple systems, asteroids spinning at their disruption limit, asteroid pairs, contact binary structures, and fast rotating complex tumblers, among others.

5.1. Heliocentric Orbits

Classical studies in dynamics have mainly focused on the heliocentric orbits of small bodies and their time evolution. In the past few decades many fundamental problems have been solved in this realm. Examples include the joint analysis of the Yarkovsky effect, resonances, and secular dynamics to clearly map out how migration of asteroids occurs within the main belt (e.g, Vokrouhlický & Farinella 2000, Bottke et al. 2001). By combining these analyses researchers now have a clear view of how the inner solar system is populated with small bodies.

New work in this area is in tracing out the implications of solar system evolution for the current distribution and dynamics of small bodies in the solar system (Minton & Malhotra 2009). The goal is to use current and predicted distributions of small bodies as tests for or against various theories of planet migration. A particularly fruitful area of exploration is the Kuiper belt (Levison et al. 2008), as the orbital structure of this population is not fully explained. Specifically, it is not understood whether the classical KBOs formed in situ beyond 40 AU or were scattered into that region from <40 AU.

The progress in this area can be made by better characterizing the classical population from observations because that will help to limit the number of theoretical possibilities. For example, the large binary fraction among classical KBOs appears to provide an interesting constraint (Parker et al. 2010, Nesvorný et al. 2011), because these loosely bound binary systems are fragile and become easily disrupted in some migration models.

5.2. Rotational Evolution

The recent detection of the YORP effect (e.g., Rubincam 2000) has paved the pathway for the deeper understanding of small body spin distributions (Taylor et al. 2007, Lowry et al. 2007, Kaasalainen et al. 2007). Research is still trying to understand the full implications of YORP on the long-term rotational evolution of small bodies. Initial studies have been made into nearly all of the topics of interest in this area, although full convergence onto a unified model of YORP and its implications remains to be achieved.

Specific areas that still need a fuller theoretical resolution and understanding include a complete model of the spin state and obliquity evolution of a small body subject to the YORP effect, especially when bodies are brought down into a slow rotation state. While there are several different possible end-states for small body rotational dynamics (Vokrouhlický et al. 2003, Scheeres & Mirrahimi 2008), the analysis of the joint obliquity/spin state convergence has not been carried out in a complete manner. Of special interest is whether a complex rotation state can significantly alter how a small body responds to the YORP effect and whether a body can be trapped into a slow rotation state for long periods of time (Vokrouhlický et al. 2007, Cicalò & Scheeres 2010).

Another topic that requires fuller resolution relates to the interactions between impacts and the YORP effect which could play an important role in the main belt. Initial investigation of this phenomenon indicates that significant non-linear interactions between these effects can occur (Rossi et al. 2009, 2010). The relative importance of these effects as a function of size has not been analyzed either, but due to the physics of these effects there must be a cross-over between YORP dominance and collisional dominance.

There also remains significant uncertainty in the level of detail in modeling required to successfully account for the YORP effect. The poster child of this is the asteroid Itokawa, which when simply evaluated should have a detectable change in its spin rate due to the YORP effect (Scheeres et al. 2007), yet this change has not been observed. Discussions have focused on more precise modeling of the thermal budget on the asteroid surface (Vokrouhlický & Čapek 2002, Mysen 2008), more precise accounting for internal density distributions (Scheeres & Gaskell 2008), and higher resolution modeling (Nesvorný & Vokrouhlický 2007, Statler 2009, Breiter et al. 2009). The presumed eventual detection of YORP on Itokawa will provide a stringent test for the precise modeling of the YORP effect, as a detailed shape model exists for this body.

The recent detection of spin state changes in comets also raises the rotational dynamics of these bodies as an interesting topic of study (Belton & Drahus 2007, Knight et al. 2010). New methods should be developed to enable the spin state propagation of cometary bodies

over long time spans, building on an averaged dynamical model such as is found in (Neishstadt et al. 2002) and motivated by recent models of cometary outgassing (Crifo & Rodionov 1997). This will enable insight into what, if any, limiting rotational behavior is expected in the presence of random outgassing over comet surfaces incorporating relaxation dynamics as well. A strong motivation for this is the intuitive involvement between rotational dynamics and comet nucleus bursting.

5.3. Long-Term Evolution of Multiple Component Asteroid Systems

A new topic that requires dynamical understanding is the long-term evolution of binary and multiple component asteroid systems in the near-Earth object and main belt populations. The binary YORP effect (BYORP) predicts that the lifetimes of binary asteroids are extremely short, on the order of 10^5 years (Ćuk 2007, McMahon & Scheeres 2010). However, this would imply an implausibly rapid formation rate for binaries, and thus alternative time evolutions of these bodies have been investigated.

Current modeling efforts are concentrating on the effect that coupled rotational and translational motion will have on the BYORP effect (Ćuk & Nesvorný 2010, McMahon & Scheeres 2010), although there has not been uniform agreement on the net effect of these interactions. What is needed in this area is an analysis of the long-term evolution of a binary system that fully accounts for all evolutionary effects that will act on an asteroid system over time. Individual analyses have looked at and compared components of these effects, but have not systematically put them all together. Such an analysis should include tidal effects (Goldreich & Sari 2009), the YORP effect on the primary (Harris et al. 2009, Fahnestock & Scheeres 2009), the BYORP effect on the secondary (Ćuk & Burns 2005, McMahon & Scheeres 2010), and spin-orbit coupling between the two bodies (Ćuk & Nesvorný 2010, McMahon & Scheeres 2010).

5.4. Rubble Piles with Evolving Rotational Angular Momentum

Related to the spin evolution of small bodies and the stability of multi-component systems is the more general question of how rubble pile bodies evolve in response to secular or abrupt changes in their total rotational angular momentum. These changes can occur slowly over time due to the YORP effect, can occur over a single rotation period of a body due to close planetary flybys, or can occur instantaneously due to impacts.

The basic mechanics of collections of bodies resting on each other are not well under-

stood. Important work has been done at the continuum level by Holsapple, indicating that strength models may play an important role in the ability of small bodies to spin rapidly, and supply some understanding of how such bodies might fail (Holsapple 2001, 2004, 2007, 2010). However, the continuum limit is a significant simplification at the size scale of these small bodies, where the discrete nature of interaction must be accounted for.

Some rudimentary theoretical work has been done investigating the basic rules that a rubble pile system must follow as its angular momentum increases over time (Scheeres 2007, 2009). Similarly, initial forays into the modeling of such systems has also been performed (Walsh et al. 2008, Sanchez & Scheeres 2011). However, systematic theories for and modeling of discrete bodies resting on each other incorporating exogenous perturbations is a challenging problem and will be central to the understanding of a number of fundamental problems that span different systems across the solar system. Specifically, the dynamics of discrete granular systems are present during the initial planetesimal formation phase of the solar system, when smaller components were initially precipitating and clumping into larger structures.

Numerical studies of these bodies have been made using hard-sphere codes (Richardson et al. 2005), however modeling the low energy, contact structure between the particles forming a rubble pile is challenging given the impulsive nature of interactions in these codes. Modifications to these simulations are being investigated that will allow these codes to be extended into this regime. More recent work has developed a modeling formulation that applies soft-sphere models for self-gravitating bodies in contact (Sanchez & Scheeres 2011), leveraging from the field of granular mechanics. The field of numerical simulation of rubble piles with changing angular momentum is still at an early stage of development, and its development will be important for these systems to be better understood. A specific challenge in this field is tracking how energy and angular momentum can be redistributed within a rubble pile as a function of its total angular momentum and the manner in which it changes.

5.5. Formation and Failure of Binary and Multi-Asteroid Systems

The rotational fission of rubble piles has been implicated in the formation of binary systems (Fig. 6; Scheeres et al. 2006, Scheeres 2007, Walsh et al. 2008) and in the formation of asteroid pairs (Vokrouhlický & Nesvorný 2008, Scheeres 2009, Pravec et al. 2010). The specific process by which a fissioned rubble pile evolves to its end state is not understood, however. Specifically, we find a diverse morphology of small body types equally subject to YORP yet not fully explained with one theoretical understanding, including binary and

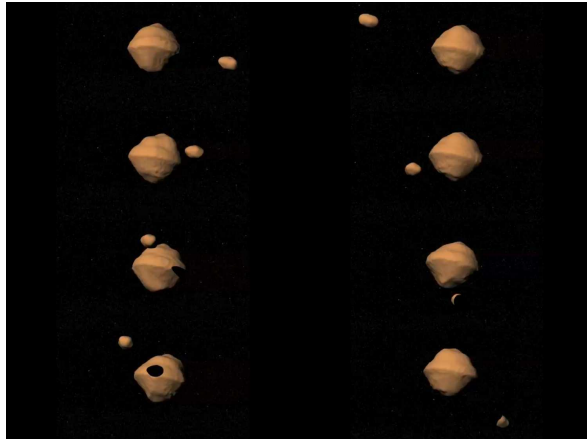


Fig. 6.— High resolution radar images reveal near-Earth asteroid (66391) 1999 KW4 to be a binary system. The ≈ 1.5 -km-diameter primary is an unconsolidated gravitational aggregate dominated by an equatorial ridge. The ≈ 0.5 -km secondary is elongated and probably denser than the primary. Figure from Ostro et al. (2006).

triple systems, contact binary systems, tumbling asteroids, reshaped asteroids, and other more specific morphologies.

Recent evidence on asteroid pairs provides interesting clues to the bi-modal mass distribution structure of asteroids that form asteroid pairs (Pravec et al. 2010). Additionally, theoretical work predicts that all initially fissioned bodies to be unstable (Scheeres 2009), whether or not they are energetically bound to each other, although the full implications of this are still being worked out. Specifically, the initial evolution of two component bodies formed by fission remains unmodeled in a detailed sense, although simple initial models have been developed and are showing that the evolution is highly chaotic and has significant spin-orbit coupling occurring over the first few days, weeks and months of these systems (Jacobson & Scheeres 2009, 2010). How this can lead to the observed small body systems is a key topic for future understanding.

5.6. Celestial Mechanics of Low Energy Systems

At the mathematical level, there is a dearth of research into celestial mechanics systems at the low energies we find for rubble pile bodies. A celestial mechanics view of the rubble pile problem would involve the imposition of a finite density for constituent bodies, making them have finite radii and allowing them to lie on each other in relative equilibria in addition to orbital equilibria. A systematic study of this problem from the point of view of rigorous mathematics could yield significant fruit, and would also provide specific results that could be used to validate and verify the performance of numerical simulations. One possible motivating thesis statement would be to evaluate all possible stationary energy configurations of celestial mechanics systems with finite radii as a function of angular momentum. Initial studies have just looked at two bodies in interaction, but could be extended to multi-body systems (Scheeres 2007).

5.7. Plasma and Weathering on the Surfaces of Small Bodies

Small bodies lie in extreme environments, and are themselves extreme and exotic locales. How these bodies interact with their external environment and what physics are important for their own evolution and structure are essentially open questions.

The general interaction of small body surfaces with the solar system environment is a current field of research. It is well known that exposure of asteroid surfaces to sunlight and the solar wind causes changes in their spectral signatures over time, called weathering. There have been many advances in understanding these weathering physics in recent decades, however a full understanding of the process and its speed is still lacking.

In a particularly interesting recent development, correlations between Earth flybys and S to Q Type transitions among NEO have been discovered (Nesvorný et al. 2005, 2010b; Binzel et al. 2010). However, the details of this process are not understood, as the initially proposed tidal interactions seem to be too weak to be responsible for mechanically altering the surface of an asteroid and exposing fresh material. This is motivating detailed investigations into the interactions of charged surfaces with a planet’s magnetosphere to ascertain whether some non-gravitational effect is either causing resurfacing or can systematically lead to a change in the spectral signature of a body.

Related to these phenomenon is dust levitation caused by plasma fields on the surface of airless bodies and charging through the photoemission effect. Dust clouds were observed on the moon and current theories link them with the surface plasma environment and charging of dust grains, although the detailed mechanisms or the necessary surface environment that

leads to levitation are not well understood. Similar levitation has also been hypothesized on asteroids (Lee 1996, Colwell et al. 2005) and invoked to explain the dust ponds on the Eros surface (Robinson et al. 2001). However, a full accounting of forces on an airless body places other restrictions on how a particle may be mobilized from the surface of the moon or an asteroid, and seems to throw some of the assumptions about how levitation physically occurs into doubt. There is currently no end-to-end theoretical explanation for this phenomenon, and thus this is ripe for additional research.

5.8. Evolution of Comet Surfaces

Recent images of comet surfaces and close-in environments have only added mystery to how their surfaces evolve and change over time. It is not an overstatement to say that each comet imaged at close range has had a markedly different surface morphology. Some theories and simple explanations of how comets work have been developed (Jewitt 2004, Goguen et al. 2008, Belton et al. 2008, Belton & Melosh 2008), however these do not provide for a uniform theory of comet surfaces that accounts for all the different observed surface morphologies. With the imminent arrival of Rosetta at its target comet 67P/Churyumov-Gerasimenko, there will be a wealth of detail not available before concerning the physical evolution and morphology of a comet’s surface. Thus, development of clear theoretical approaches to this problem would be able to be tested or evaluated with this coming data set.

5.9. Physical Forces in Micro-Gravity Settings

The surfaces and interiors of small bodies can have ambient accelerations less than micro-gravity due to their small mass and potentially rapid spin rates. When the weights of objects become vanishingly small it is feasible that other physical forces and effects may play significant roles. These include self-gravitational attraction between bodies, van der Waals cohesion, cold welding of materials, and a variety of other effects that may not be relevant for larger bodies. Theoretical predictions have been made concerning these effects (Scheeres et al. 2010), but laboratory tests must still be made to fully evaluate how the near absence of gravity modifies the physics of interaction between bodies.

Of specific interest relating to this are the bulk constitutive laws appropriate for small bodies in the micro-gravity regime. Specifically, a better understanding of how tidal dissipation occurs in these systems and how interiors of small bodies will strain in response to stress fields are required. Classical theories tend to be related to deformation of a continu-

ous media. However, for small bodies tribology effects must be included and considered in order to develop a full model of these interactions. Initial work in this area has been done (Holsapple 2010, Goldreich & Sari 2009), yet a specific grounds-up physical analysis of this effect must still be made.

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